# Equivalent Static Wind Loads on Tall Buildings with Soil - Structure Interaction or Base Isolation by Using a New Model for Estimating the Wind-Induced Responses



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| 著者 | 王 天元 |
| 号 | 55 |
| 学位授与機関 | Tohoku University |
| 学位授与番号 | 工博第4416号 |
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| | おう　てんげん |
| 氏　　　　　名 | 王　　天元 |
| 授　与　学　位 | 博士（工学） |
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| 指　導　教　員 | 東北大学教授　植松　康 |
| 論文審査委員 | 主査　東北大学教授　植松　康　東北大学教授　井上　範夫<br>東北大学教授　持田　灯　教授　　薛　松濤（東北工業大学） |

# 論文内容要旨

Wind loads may dictate their structural design of tall buildings, especially in low seismological active regions. The wind loading is a complex issue, which is not yet analytically tractable. Engineering disciplines have involved statistical analysis of wind records, meteorological description of the atmospheric boundary layer, aerodynamics of flow around bluff bodies, and dynamic response of structures and their possible feedback into the flow. In the structural design of tall buildings, the wind loads are usually represented as 'equivalent static wind loads (ESWLs)'.

The aspect, which has most eluded analytical treatment, is that of the aerodynamic response. Some methods for predicting the aerodynamic forces on civil engineering structures have been developed and utilized in building codes and standards. However, these methods are conventionally based on an assumption that the structures are fixed to rigid base; in another words, the foundation is supported on the bedrock. Most building codes and standards are specified based on this assumption. No specifications are given to the effects of soil-structure interaction (SSI) on the wind-induced responses and the resultant load estimation as well as to the wind loads on tall buildings with some artificial technology to allow the motions of foundation, such as base isolation.

Recently, many tall buildings have been constructed on soft soil, e.g. in Shanghai, China. Therefore, it is hoped to develop a new model for estimating the wind-induced responses of tall buildings with consideration of the soil-structure interaction. This subject has been investigated by several researchers, e.g. Novak (1974, 1977), Novak and Hifnawy (1983), Lin and Wu (1983), and Halabian et al. (2003). However, there are many problems still unsolved. A proper dynamic response analysis of a tall building with soil-structure interaction requires adequate consideration of the following two aspects: that is, (a) the lengthened fundamental period of the building due to the soft soil; and (b) the radiation damping due to the deformation of soil around and underneath the foundation due to the energy radiation between the structure and soil. The soil-structure interaction results in energy dissipation through radiation of waves into the soil medium.

Base isolation is a mature and popular technique to migrate the damage caused by strong earthquakes (Naeim and Kelly, 1999). Traditionally, this technique has been applied to only low-rise and medium-rise buildings. However, recently the base isolation has also been applied to tall buildings. Many tall base-isolated buildings have been constructed in Japan; some of them are taller than 100 m. Wind forces on such tall buildings, particularly on the isolators, become significant. In most cases, due to the initial stiffness of isolators, the fundamental vibration period and system damping within the pre-yielding range of the isolators are different from those of the building without base isolation. The initial stiffness of the isolators lengthens the fundamental vibration period of the building, which makes the building more sensitive to fluctuating wind loads than that without base isolation (Henderson and Novak, 1989). Therefore, it is hoped that a new method will be developed to analyze the wind-induced responses of tall base-isolated buildings and the isolators.

The most important thing for the buildings with soil-structure interaction or base isolation is that the fundamental natural period is lengthened, which results in more wind energy transmitting into the buildings. Conventional approach of structural design of buildings without considering this feature may underestimate the design wind loads. Furthermore, the conventional design approaches corresponding to a single degree of freedom cannot be applied to buildings with base motions, because the superstructure is subjected to additional acceleration induced by the base motions.

Based on the above discussion, the purposes of this dissertation are summarized as follows:

(1) To develop a new and strict mathematical model for predicating the wind-induced response of conventional tall building, which is derived theoretically and has a clear physical meaning. This model can also be applied to unconventional buildings with base motions.

(2) To investigate the characteristics of wind-induced responses of tall building with soil-structure interaction and to develop a model for predicating the equivalent static wind loads.

(3) To develop a practical model for predicating the equivalent static wind loads on tall building with base isolation.

The dissertation consists of the following seven chapters:

CHAPTER 1 Introduction

The objectives, background of the study are described. The contents of each chapter are briefly presented.

CHAPTER 2 Background

A review is made of the studies on the aerodynamic response and its load estimation of tall buildings. First, the aerodynamic response phenomenon of structures is described. Wind action on buildings is conveniently separated into the mean and fluctuating components. The experimental models in wind tunnel, including aerodynamic and aeroelastic models, are introduced. Some researchers have developed the theory of wind-structure coupling response. The traditional design approaches to the along-wind and across-wind responses of tall buildings include the gust loading factor methods based on the displacement or base moment. The equivalent static wind load technique is introduced, which is an important content of this dissertation.

CHAPTER 3 Wind Models for Along-Wind and Across-Wind Responses

This chapter contains the basic theory of the wind models in the along-wind and across-wind directions. For the along-wind direction, focus is on the power spectrum density of oncoming wind and the aerodynamic admittance function. On the other hand, due to the wind turbulence as well as to the vortex in the wake, the mechanism of the across-wind force on tall buildings has not been clarified yet. Therefore, the wind model is generally based on the base moment obtained from high frequency base balance in wind tunnel experiments, assuming that the target mode shape of the building is linear. Furthermore, mode shape corrections are described and the formula for correction factors is provided.

CHAPTER 4 A New Model for Estimating Wind-Induced Responses of Tall Buildings

A new model including the background and resonant components and their cross-term of the wind-induced response of tall buildings is theoretically derived based on the 'Indirect method'. First, the history of the development of the conventional models is overviewed. The starting point of the conventional models is discussed in detail. Then, the basic principle of aerodynamic response is defined, as was done in the conventional models, only for SDOF system. The new model is derived based on a strictly mathematical process. The background component is essentially related to the characteristics of external wind loads, while the resonant component is regarded as the sum of the inertial and damping force terms; In addition, the cross-term between the background and resonant components is formulated. Comparisons are made between the conventional and new models for the along-wind and across-wind responses.

Finally, some suggestions and useful conclusions are presented. Regarding the along-wind responses, the "Original definition" models provide relatively accurate estimations when the upper limit of integration for calculating the background component is set to the fundamental natural frequency of the building. Regarding the across-wind responses, on the other hand, the "Original definition" models underestimate the total responses. Using this new model, we can estimate the equivalent static load effect not only on the conventional buildings but also on unusual buildings with soil-structure interaction or base isolation. The new model provides the theoretical basis of the following chapters, i.e. the wind-induced responses of tall building with soil-structure interaction (Chapter 5) or base isolation (Chapter 6).

CHAPTER 5 ESWLs on Tall Buildings with Soil-Structure Interaction

This chapter proposes a model for predicting the equivalent static wind loads on tall buildings with soil-structure interaction. First, the background of soil-structure interaction, including problem definition and the application to earthquake resistant design, is shown. Previous studies of this problem are reviewed. The frequency dependent impedance function of foundation is described based on the elastic half-space theory of soil. Veletsos and Verbic (1973) model and the Bielak (1975) model are adopted as the impedance functions of foundations for surface footing and embedded foundation, respectively. Then, a mathematical model for tall buildings with soil-structure interaction is derived based on the spectral equivalent method. The mechanical admittance functions of tall buildings with soil-structure interaction are investigated based on some numerical examples. An empirical formula of the mechanical admittance function is proposed by using the effective natural frequency and damping. A parametric study indicates that the effective period $\tilde{T}_1$ of the system increases as the soil stiffness decreases. However, the soil-structure effect is generally small for practical conditions. Furthermore, as the soil stiffness decreases, the effective damping ratio $\tilde{\zeta}_1$ decreases, especially for the surface footing. On the other hand, for the embedded foundation with high embedded ratio, the effective damping $\tilde{\zeta}_1$ increases when the structural damping is low, e.g. less than approximately 1 %. The values of $\tilde{T}_1$ and $\tilde{\zeta}_1$ are also affected by the aspect ratio $Ar$ of the building, the embedded ratio $e$ of foundation and the mass density ratio $\rho_{s/m}$, but less sensitive to the exponent $\beta$ representing the vibration mode of superstructure.

Finally, based on the above discussion, the equivalent static wind loads on tall buildings with soil-structure interaction effect are derived. Some numerical studies show the efficiency of the model. Furthermore, the results indicate that the SSI effect leads to underestimation of the design wind loads on tall buildings. Regarding the along-wind responses, the difference in the resonant component is not more than 5 % between the results with and without the SSI effect. However, for the total response, including the mean and the background component, the difference is not more than 2 %. Regarding the across-wind responses, on the other hand, the difference in the resonant component is up to approximately 10 %; the difference in the total response is also up to approximately 10 %. The difference is more significant for lighter and more flexible buildings.

CHAPTER 6 ESWLs on Tall Buildings with Base Isolation

This chapter proposes a model of the equivalent static wind load for base-isolated buildings. The procedure of analysis is the same as that of Chapter 5. First, the previous work in wind-induced responses of structures with base isolation is reviewed. A simple method or model for predicating the wind-induced responses of tall buildings with base isolation are discussed based on a principle that the wind-induced response of the isolators is within pre-yielding range. Then, the mathematical model of the wind-induced responses of tall buildings with base isolation is derived, in which the mechanical admittance functions of base-isolated building system are considered. The parametric studies of the effective period and damping are made and the simple formulas for predicating them are proposed. Finally, based on the above discussion, a model for predicting the equivalent static wind loads is derived. A design procedure is also proposed. Following this procedure, some numerical studies are made to demonstrate the efficiency of the model.

CHAPTER 7 Conclusions

The most important conclusions of this dissertation are summarized. The topics unsolved and the prospects of future studies to be done are shown.

# 論文審査結果の要旨

本論文は，地盤との連成あるいは免震層を有する高層建物の風応答評価に対して，基礎のスウェイやロッキングを考慮した新しい評価手法を提案し，通常の耐風設計で用いられる「等価静的風荷重」の定式化を行ったものである。これにより，地盤との連成や免震層を有する高層建物に対しても従来と同様の枠組みでの風荷重評価を可能とした。このような建物に対しては，通常風洞実験から得られた風外力の時刻歴データを用いた時刻歴応答解析が一般に行われているが，それには多大な時間と労力が必要となる。それに対して，本研究で提案した方法を用いることで，通常の耐風設計と同様，周波数領域での解析が可能となる。

確率統計手法に基づく「等価静的風荷重」の概念は 1960 年代にダヴェンポートにより提案され，その後様々な研究者によって改良が為されてきた。それらは現在の建築基準法や日本建築学会「建築物荷重指針」における風荷重算定式の基礎となっている。しかし，それらはいずれも建物の基礎が剛な地盤に固定されているという仮定に基づいており，軟弱地盤の上に建てられた高層建物や免震層を有する高層建物のように，基礎のスウェイ，ロッキング運動を伴う構造物に適用することは困難である。近年，中国・上海のように，軟弱地盤上に高さ数百メートルもの高層建物が多数建設されている。また，低層や中層建物だけでなく高層建物にも免震構造が利用されるようになってきた。このような建物では，構造設計上風荷重が支配的な荷重となり，簡便で合理的な解析手法の開発が望まれていた。本論文では，理論的なアプローチによりこの課題に取り組み，従来とは異なる新しいモデルを提案した。

本論文は全７章よりなっている。

第１章は序論である。本研究の目的，背景を述べた。また，論文構成と各章の概要をまとめた。

第２章では，高層建物の風応答とその荷重評価に関する研究のレビューを行った。ガスト影響係数法をはじめ，風方向および風直交方向応答やそれらの風荷重評価法，風圧・風力模型や空力弾性模型を用いた風洞実験法を概説した。

第３章では，高層建物に作用する風方向および風直交方向の風荷重のモデル化について，既往の研究成果に基づき纏めたものである。

第４章では，高層建物の風方向および風直交方向応答に対し，理論的考察に基づき新しい解析モデルを提案した。共振成分を慣性力と減衰力の和として表現したこと，および，準静的成分と共振成分の相関を考慮したことで，より厳密な応答評価が可能となった。また，従来の手法では扱うことができない地盤との連成や免震層を有する場合にも適用可能となった。

第５章では，地盤と構造との連成を考慮した高層建物の風応答解析に対し，第３章で提案したモデルを適用した。連成効果が建物の固有振動数や減衰に及ぼす影響を理論的に示した上で，いくつかのモデル建物の応答解析結果を示した。さらに，等価静的風荷重の評価式を与えた。

第６章では，免震層を有する高層建物の風方向および風直交方向応答に対し，第３章で提案したモデルを適用した。第５章と同様の考え方に基づき，メカニカルアドミッタンスの数学モデルを示した。また，パラメトリックスタディにより，風応答性状を明らかにすると共に等価静的風荷重の評価式を与えた。

第７章は結論である。

以上，要するに本論文は，地盤との連成や免震層を有する高層建物の風応答や風荷重に対して新しい評価手法を提案したものであり，建築構造工学の発展に寄与するところが大きい。

よって，本論文は博士(工学)の学位論文として合格と認める。